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Fine Root Biomass and Soil Chemistry in the 'Ome' Agroecosystem of Buton Karst, Indonesia

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The "Ome" agricultural system in the karst region has unique characteristics that influence root biomass production and soil chemical properties based on the duration of land abandonment. This research aimed to investigate the relationship between the root biomass production and soil chemical properties of the Ome agricultural system in the karst land area of Central Buton. Method: This study employed a field survey method where soil sampling was conducted at three ages of "Ome," at 10-, 20-, and 40-years post-abandonment. Soil samples were collected using quadrats measuring 25 x 25 cm at a depth of 10 cm. The fine roots, which had been cleaned, were subsequently sorted into living roots (biomass) and dead roots (necromass) and then dried. The chemical properties of the soil analyzed include pH, CN, total N, P_2O_5, available P, NH_4^+, NO_3, K, Ca, Mg, C, N, and Cation Exchange Capacity (CEC). Results: The pH and nitrate (NO_3) parameters at the "Ome"age of 40 years are significantly greater than those at the other ages. Higher increases in pH and Nitrare at 40 years of land age indicated significant change in soil chemistry related to the stages of vegetation succession, thus accumulating litter that absorbs soil rich in K and Mg, which plays a role in increasing soil pH and will increase nitrogen in the soil. There are no significant differences observed at the ages of 10 and 20 years. Fallen "Ome" land is divided based on the degree of fallow, which varies the amount of fine root biomass, necromass, and total fine root mass. Fine root biomass is correlated with several soil characteristics, such as Ammonium (NH_4^+) Nitrate (NO_3) and Carbon (C), which may or may not influence the fine root development. Conclusions: The potential of root biomass in the "Ome" agricultural system in karst areas is positively correlated with indices of soil chemical properties that may vary with different "Ome" abandonment durations.
Keywords: Soil health, organic matter, soil chemistry, root biomas, nutrient cycling, root necromass

INTRODUCTION

Karst regions are fragile ecosystems with low fertility, quick drainage, low organic matter content, and sparse vegetation coverage (Li *et al.*, 2022). Land use and time since abandonment are among the major factors impacting the properties of karst soils (Pan *et al.*, 2022). Historically abandoned components generally undergo natural recovery over time (Quintas-Soriano *et al.*, 2022), during which the surrounding soil physical and chemical characteristics change, such as by weathering, accumulating organic matter, and due to microorganism activity (Usharani *et al.*, 2019). On the other hand, land that has been temporarily abandoned after agricultural practices or other industrial exploitations is as usually on the road toward degradation, with major impacts on soil either in the physical properties, nutrients, or plant fine roots dynamics. Karst regions have unique challenges related to agricultural resource management, particularly with regards to water availability and soil (Wu and Wang, 2024). One of the agricultural systems implemented by the community in the karst region of Gu District, Central Buton, Southeast Sulawesi, is "Ome" (*local language*). The "Ome" system begins with the clearing of land covered with tree/shrub vegetation using a slash-and-burn method, following by planting corn and cassava, with the land cultivated for approximately four years without fertilization. Subsequently, the land is abandoned, and new land is opened. The next phase of land clearing occurs in previously abandoned areas that have been left for about 15 years, allowing for the growth of higher vegetation (trees and shrubs) during succession.

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The "Ome" agricultural system developed in karst areas is a community adaptation effort to regulate land with distinct traits, like high porosity, low nutrient content, and susceptibility to erosion and drought (Xiao *et al*., 2023). A great product of this system that keeps the soil fertile is the root biomass, the presence of organic matter improves the chemical properties of the soil (Geng and Jin, 2022). But the special and dynamic soil chemistry properties in karst areas can affect root biomass production (Xu *et al*., 2021). Context the "Ome" agricultural system, the use of fine root biomass plays a key role in intensive agricultural systems growing in the harsh karst ecosystem.

Fine roots are considered as a major functional component in forest ecosystems; they are involved in the nutrient absorption, carbon cycling, and overall forest productivity (Fang *et al*., 2025). Root biomass (especially fine roots) is produced which helps in nutrient cycling and in the decomposition processes, which allow for nutrients to be released into the surrounding soil (Solly *et al*., 2018). Root biomass contributes a large portion of the biosphere, approximately 30% of aboveground biomass (Du *et al*., 2019). Fine roots (<2 mm in diameter) are integral to the cycling of nutrients, water, and other elements, and contribute to soil organic matter as they decay (McCormack *et al*., 2017). These roots belong to and interact with soil environment, via the exudates of labile C compounds from live roots and decomposition of dead roots (McCormack *et al*., 2015). They normally develop in distinctive soil profile depth layers and have a high sensitivity to different soil physical and chemical properties, like texture, compaction, pH, and nutrients (Tian *et al*., 2024). Fine root growth, senescence, and decomposition processes collectively are responsible for root population dynamics including living fine root biomass and dead root necromass (Wang *et al*., 2018). In karst land ecological systems, the relationship between root traits and soil chemistry is the primary driving factor of agricultural productivity (Xu *et al*., 2021).

Within the context of the "Ome" agriculture, exploring how soil chemical properties impact root biomass production can provide valuable insights for the establishment of sustainable soil management strategies adapted to karst-based agriculture system. It is hoped that by clarifying the benefits of root biomass in maintaining soil life, it will be possible to design agricultural management practices that are both affective and environmentally sustainable in supporting the food security of local communities.

MATERIALS AND METHOD

***Location of the study*:** The research was carried out on agricultural land that uses the "Ome" system in Lakudo District, Central Buton District, Southeast Sulawesi Province, Indonesia. The study site corresponds to a karst region, with cambisol soil types and slope from 5 to 8%, 8-25% and with annual rainfall of 2500-2750 mm. The age of abandoned land within the "Ome" system was determined through an initial survey conducted via interviews with residents. The respondents included two farmers and one community leader. The selection criteria for respondents were: 1) aged over 60 years, 2) employed the "Ome" agricultural system, 3) knowledgeable about land ownership, and 4) still practicing the "Ome" agricultural system at the study location.

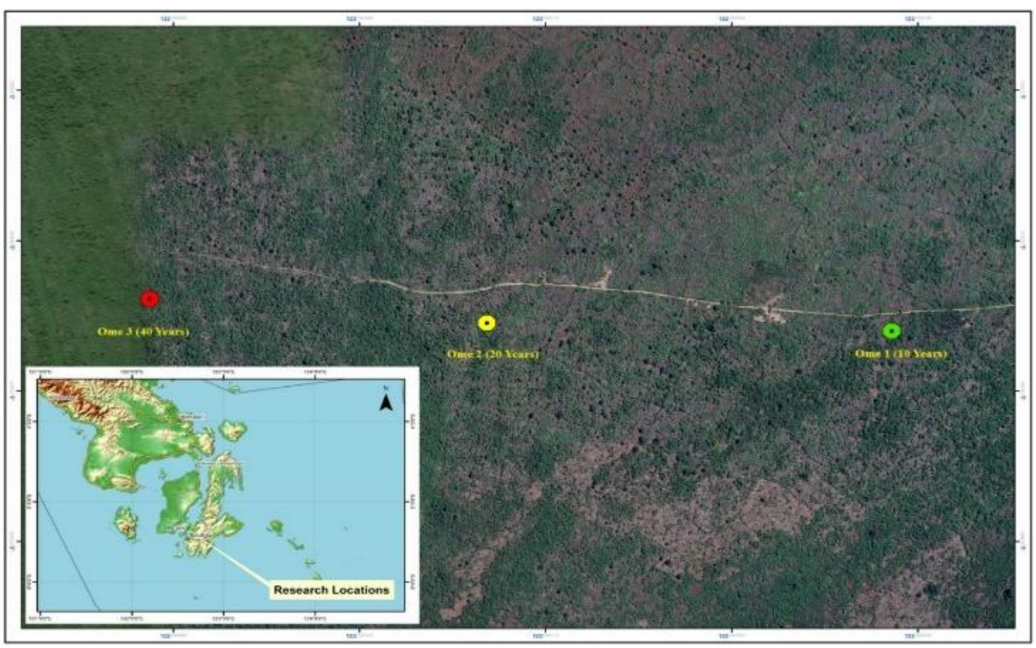

Figure 1. Research locations based on "Ome" age.

Based on the results of interviews, observations, and site visits to the "Ome" locations, three sites were determined based on "Ome" age:

a. "Ome 1," which has been abandoned for approximately 10 years, located at longitude 122°36’0.57” East and latitude 5°20’39.63” South.
b. "Ome 2," which has been abandoned for approximately 20 years, located at longitude 122°35’39.33” East and latitude 5°20’39.15” South.
c. "Ome 3," which has been abandoned for approximately 40 years, is located at longitude 122°35’21.63” East and latitude 5°20’37.70” South (Figure 1).

***Determination of transects*:** Transects for sampling were determined based on the vegetation conditions at each location according to the age of abandonment of the "Ome". The research location of three age categories of “Ome” (Figure 1), with a total of three transects for each age category, each measuring approximately 215 m, was systematically established on the left and right sides of the transect. Each transect includes three observation plots spaced approximately 100 m apart, each measuring 5 x 5 meters. Each observation plot consists of five subplots, each measuring 25 cm x 25 cm and with a depth of 10 cm, serving as soil sampling points. The five subplots are composites of a single sample. Within one observation transect, there are three soil samples, resulting in a total of nine (9) soil samples for replicates were used each age of “Ome”. The scheme for the installation of transects and plot can be seen in Figure 2.

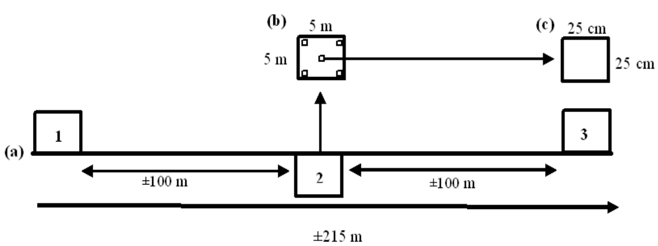

Figure 2. Design of Transect/Observation Plot Layout
Note: (a) Transect Model, (b) Sample Plot Model, and (c) Soil Sampling Model using a quadrant measuring 25 cm × 25 cm.

***Sample collection*:** Soil samples from each plot at a depth of 10 cm were collected into plastic bags and taken to the laboratory. Soil sampling was carried out at a depth of 10 cm for several reasons, namely that at a depth of 10 cm it is usually a place where microorganisms and fine roots are still active and this soil layer is where organic matter accumulates and the decomposition process takes place (Liu *et al.*, 2020). Dominant plants in the karst area in the “Ome” system tend to adapt will shallow roots that spread to find nutrients in thin soil layers (Fang *et al.*, 2025). The method of cleaning and sorting fine roots is done by cleaning the fine roots from the soil sample by washing them with running water using a 2 mm sieve to separate the roots and soil particles. Then the washed roots are cleaned again manually using tweezers to remove the remaining soil that sticks to them following the method outlined by Wang *et al.* (2018).

Fine roots were considered three categories: living roots (biomass), dead roots (necromass) and total fine root mass (biomass + necromass). Identification was primarily based on flexible and elastic consistency between live roots showing a lighter color to slightly brown steles and dead roots that had a crunchy consistency and a dark brown to black stele (Du *et al.*, 2019). Fine root biomass was measured as root samples were washed, dried at 70 °C for 24 h to constant weight, and expressed as g m-^{2}. The roots were weighed before and after drying then the initial and final mass were calculated using a BEL analytical balance laboratory, Faculty of Mathematics and Natural Sciences (FMIPA), Halu Oleo University. The following physical and chemical properties were measured from the soil: pH, organic carbon, total nitrogen, total and available phosphorus, ammonium, nitrate, potassium, calcium, magnesium, carbon content and cation exchange capacity (CEC). Each subplot was sampled by compositing 2 kg of soil, passing through a 5 mm sieve, and sending it to the laboratory for these analyses.

***Statistical analysis*:** Ome land abandonment stages were evaluated by a multi-way Analysis of Variance (ANOVA) for soil properties and fine root biomass. A Least Significant Difference (LSD) test was used to identify significant differences between habitat treatments at the 95% confidence level. Analyses for relationships between soil characteristics and root biomass were conducted using a two-tailed Pearson correlation test. Digital Ecological analysis through Principal Component Analysis (PCA) was performed with Past software version 4.03 to evaluate the effect of different types of habitat on root biomass. Statistical analyses were performed using SPSS version 23.0.

RESULTS

***Influence of soil chemical properties at various "Ome" ages on root biomass*:** The chemical properties of the soil at various ages of "Ome" at the research location are presented in Table 1. The chemical properties of the soil that influence the different ages of "Ome" observed include pH and nitrate (NO_3).

The results of soil analysis showed that pH and NO_3^- contents differed significantly ($P<0.05$) among different "Ome" land abandonment stages. Other soil chemical properties did not differ statistically significantly. Single soil chemical characteristics played an important role in the fine root biomass development. For example, soil pH, may not change much as this variable could still be influenced by decomposition of organic material and nutrient mobilization at that time. Results: Other Studies Table No. 1 Soil and pH Trends with Land Colonization - pH of soil shows that longer periods of neglect lead to a reduction in acidity Soil organic carbon peaked at O20 "Ome" and was the lowest at O10. For

total nitrogen, no significant differences were observed between stages, with similar values consistently seen across all time points. The highest levels of total P_2O_5, available phosphorus and potassium (K) were observed at the 20-year stage with the lowest levels at 10 years. Which assessment years had the highest level of ammonium (NH_4^+) and the lowest? The highest was the 40-year "Ome" and the lowest was the 10 years. Indeed, calcium (Ca) and magnesium (Mg) levels were both highest at age 40. Conversely, carbon (C), nitrogen (N) and cation exchange capacity (CEC) showed maximum values in the 10-year abandonment stage.

Table 1. Chemical properties of soil at various ages of "Ome".

No.	Chemical Properties	Age of Ome		
		±10 Years	±20 Years	±40 Years
1	pH	7.37±0.05^b	7.13±0.05^a	7.13±0.05^a
2	C-Organik	3.11±0.24	3.23±0.34	3.21±0.29
3	Total Nitrogen	0.32±0.01	0.3±0.02	0.32±0.02
4	Total P_2-O_5	19.50±1.10	20.63±1.85	18.96±1.56
5	P – Available	15.36±0.82	17.18±0.38	15.73±1.93
6	Ammonium (NH_4^+)	1.65±0.09	1.66±0.13	1.81±0.13
7	Nitrate (NO_3)	2.07±0.10^b	1.74±0.12^a	1.78±0.16^a
8	K	0.43±0.04	0.54±0.08	0.44±0.10
9	Ca	18.51±1.30	18.1±1.95	20.44±0.28
10	Mg	7.07±1.34	7.29±1.55	8.67±0.33
11	C	7.99±0.19	7.12±0.82	7.51±0.66
12	N	0.83±0.02	0.68±0.12	0.47±0.19
13	Cation Exchange Capacity (CEC)	27.39±3.27	23.54±4.80	26.11±3.41

Note: Treatments with the same letter in each row indicate no significant difference (LSD test, $P < 0.05$).

Effect of the age of "Ome" on fine root biomass: Fine root biomass differs at ages 10, 20, and 40 of "Ome." Fine root biomass data are shown in Table 2.

Active fine root biomass differed significantly ($P<0.05$) between the 10- and 40-year "Ome" stages (Table 2). The age of the "Ome" land affected fine root biomass significantly in these two periods. Unlike the case with fine root necromass, the differences among abandonment ages were not statistically significant. This may be partly due to higher average necromass values per transect at the 20- and 40-year stages. On the whole, necromass values were much lower than fine root biomass, likely resulting from the greater age of the "Ome" plots, which favor denser vegetation and closed canopies that support a growing root system. As emphasized by Wang *et al.*, (2017), as such taller vegetation of equal stem density typically supports more living biomass, which subsequently needs more fine roots to promote. The increase in root mass over time ($P<0.05$) (particularly for the lands abandoned for 10 and 40 years).

Table 2. Fine root biomass at various ages of "Ome".

Age of "Ome"	Transect	Fine Root Biomass (g/m^2)		
		Root Biomass	Root Necromass	Total Root Mass
10 Years	1	3.147±2.79^a	0.198±0.14^a	3.345±2.93^a
	2	10.006±3.02^b	1.415±2.01^a	11.420±4.88^b
	3	2.746±0.67^a	0.320±0.12^a	3.067±0.56^a
20 Years	1	11.087±8.63^a	1.474±1.38^a	12.561±9.97^a
	2	7.377±1.25^a	2.411±1.65^a	9.788±1.98^a
	3	4.411±3.04^a	0.526±0.37^a	4.938±3.23^a
40 Years	1	18.758±2.92^b	1.210±0.85^a	19.968±2.97^b
	2	8.292±2.95^a	1.207±1.71^a	9.499±4.44^a
	3	7.187±0.63^a	1.315±0.94^a	8.502±0.33^a

Note: Treatments with the same letter in each row do not differ significantly (ANOVA with LSD test, $P < 0.05$).

Chemical properties of soil and fine roots: The physicochemical properties of soil can involve fine rooting, which can impact plant productivity and soil nutrient cycling. Table 3 shows the relationships between coarse root biomass and soil physical properties.

The results indicate that fine root biomass at the age of 20 years has a significant (negative) correlation with NH_4^+, NO_3, and C with these soil properties ($P <0.05$). At the "Ome" age of 10 years, fine root biomass shows a positive correlation with pH, CN, total N, NO_3, K, and Mg, although not significant, and a negative relationship with Total P_2O_5, P-available, NH_4^+, Ca, C, N, and CEC. Root necromass correlates positively with pH, C-Organik, NO_3, K, and Mg, while negatively correlating with total N, Total P_2O_5, available P, NH_4^+, Ca, C, N, and CEC. Meanwhile, total fine root mass shows a positive correlation with pH, C-Organik, total N, NO_3, K, and Mg. At the "Ome"age of 40 years, fine root biomass correlates positively with Ca, C, N, and CEC. Root necromass correlates positively with CN, total N, Total P_2O_5, P- available, NH_4^+, K, Ca, Mg, and N. Total root mass correlates positively with NO_3, Ca, C, N, and CEC (Table 3).

Influence of soil chemical properties on fine roots: The effect of the physical-chemical properties of the soil on fine roots at the research site was analyzed using PCA, as presented in Figure 3.

The PCA yields a first axis that explains the most variance (55.361%) and a second axis that explains the remainder (44.639%). Soil properties that drive fine root bio-mass, necromass, and total root mass includes pH, organic carbon, total nitrogen, total P 2 O 5, available phosphorus, ammonium (NH_4^+), nitrate (NO_3^-), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), carbon (C), nitrogen (N), and cation exchange capacity (CEC). Specifically, fine root biomass and total root mass were positively correlated with NH_4^+ and Mg^{2+} concentrations in soils from "Ome 3," representing land that had been abandoned for 40 years (PCA results) (Figure S1). Soil pH and other chemical parameters (NO_3^-) are

Table 3. Soil chemical properties and their relationship to fine root biomass.

Fine Root Biomass	Soil Chemical Properties												
	pH	**C-Organik**	**N-Total**	**Total P_2-O_5**	**P-Available**	**NH_4^+**	**NO_3**	**K**	**Ca**	**Mg**	**C**	**N**	**CEC**
Age of Ome (10 Years)													
Fine Root Biomass	0.542	0.517	0.101	-0.840	-0.474	-0.237	0.066	0.909	-0.941	0.454	-0.182	-0.141	-0.460
Fine Root Necromass	0.419	0.632	-0.039	-0.908	-0.346	-0.999	0.205	0.958	-0.884	0.574	-0.043	-0.278	-0.580
Total Fine Root Mass	0.525	0.534	0.082	-0.851	-0.456	-0.218	0.086	0.917	-0.934	0.471	-0.163	-0.160	-0.478
Age of Ome (20 Years)													
Fine Root Biomass	-0.832	-0.387	-0.958	0.801	-0.968	**-0.998***	**-0.998***	0.964	0.968	0.980	**-0.999***	-0.977	-0.996
Fine Root Necromass	-0.868	0.652	-0.685	0.893	-0.657	-0.503	-0.503	0.192	0.209	0.258	-0.414	-0.243	-0.365
Total Fine Root Mass	-0.868	0.652	-0.685	0.893	-0.657	-0.503	-0.503	0.192	0.209	0.258	-0.414	-0.243	-0.365
Age of Ome (40 Years)													
Fine Root Biomass	-0.696	-0.996	-0.983	-0.991	-0.775	-0.984	0.914	-0.965	0.110	-0.941	0.637	0.591	0.951
Fine Root Necromass	-0.213	0.622	0.696	0.658	0.964	0.691	-0.844	0.752	0.767	0.238	-0.995	0.346	-0.784
Total Fine Root Mass	-0.702	-0.996	-0.982	-0.990	-0.750	-0.983	0.910	-0.963	0.118	-0.943	0.631	0.597	0.948

Note: *P <0.05; ** P <0.01.

significantly ($P<0.05$) affected with the advancement of "Ome" age (Table 1). These soil chemical characteristics are particularly influenced by the development of fine root biomass. For example, increased mineralization of organic material in the deeper soil layer or leaching and redistribution of nutrients may cause soil pH to decline, suggesting that soil acidity typically increases over time with land age.

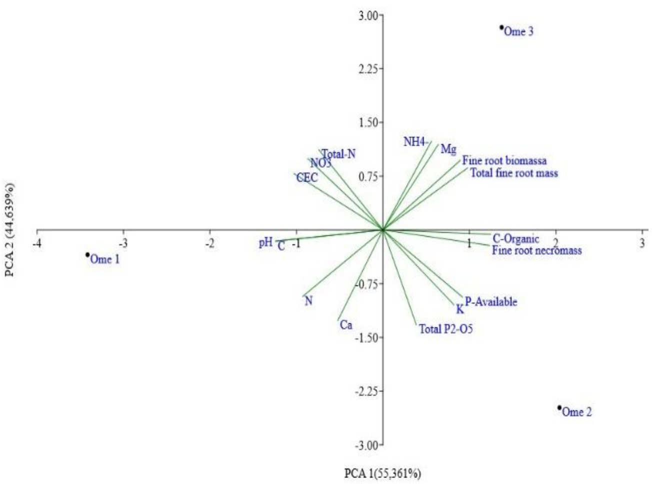

Figure 3. Principal component analysis (PCA) of fine roots at "Ome" age of 10 years, 20 years, and 40 years with soil properties.

DISCUSSION

***Effects of soil chemical properties on root biomass at different "ome" ages*:** Across the various "Ome" ages, soil chemical properties are the most dominant factor affecting fine root biomass in karst regions. Soil chemical properties using "Ome" of increasing age, as shown in Table 1 for this study In fact, pH and nitrate (NO_3) have much higher values at the 40 years old "Ome" than at the other "Ome" ages. Differences are not significant at the 10- and 20-years "Ome" ages (Su *et al.*, 2019). According to Wang *et al.* (2019) the region's soils are highly calcareous and the soil exhibits high pH and calcium levels but is low nitrogen (N), phosphorus (P), and along with additional elements. These results suggest that soil pH may play a significant role in influencing the age of "Ome" via fine roots because the productivity and turnover of fine roots are related to soil acidity. According to (Lu et al., 2023), this phenomenon is due to the calcareous nature of the soil, which is common in the karst region, where soil nutrients become depleted over time. The results also reveal that land abandoned longer accumulates much more organic matter because of degradation of older crop debris and fine roots. The aggregation of such organic material takes heed of the availability of nitrogen, phosphorus, and potassium thereby enhances fine root development. Research by Su *et al.* (2019) shows that nutrient level is directly affected by the succession of vegetation in karst area with poor soils and high heterogeneity (Su *et al.*, 2019; Zhao *et al.*, 2019). Soil nitrogen content generally rises with land use change when forest vegetation shifts from grasslands, shrublands and secondary forests to primary forests. In vegetation succession,

larger plant productivity and litter biomass lead to increasing organic matter input into the soil (Wasyliw and Karst, 2020).

***"Ome" age effects on fine roots*:** Fine root biomass, necromass and total fine root mass varied across "Ome" age. The data in Table 2 show that average fine root biomass at the "Ome" age of 10 years varies widely, averaging between 2.746 ± 0.671 and 10.006 ± 3.021 g/m². Fine root biomass shows significant increases as well, and although it peaks in transect 2 a value of 10.006 g/m² is reached in this segment of the transect ($p < 0.05$) but not in transects 1 and 3. However, at the lower of the "Ome" age of 20 years, while there is variance, fine root biomass is relatively more homogenous than in the "Ome" age of 10 years. We found that the fine root biomass is 11.087 ± 8.638 g/m² in transect 1, being higher than at 10 years. However, in transects 2 and 3, the biomass values are lower (7.377 ± 1.255 g/m² and 4.411 ± 3.039 g/m²). This means that for the "Ome" age of 20 years, while some individuals have developed high fine root biomass, many plants lack strong fine root growth (Solly *et al*., 2018). At the "Ome" age of 40 years, fine root biomass further increases, with transect 1 recording the highest average of 18.758 ± 2.921 g/m². This indicates that at the "Ome" growth phase of plants (40 years), they could have been at the optimal growth phase of the fine roots. However, similar to the age of 20 years, the fine root biomass values in transects 2 and 3 tend to be lower, although still within a higher range compared to the age of 10 years (8.292 ± 2.954 g/m² and 7.187 ± 0.633 g/m²). Overall, longer-abandoned "Ome" ages appear to be associated with increased fine root biomass in some transects, although not all individuals exhibit uniform results. Previous research by Wang *et al*. (2018) indicates that successional status significantly affects fine root dynamics, and factors such as stand density, tree age, and successional status should be included in large-scale studies to enhance the utility of fine root biomass and necromass data. Fine root biomass in all three locations increases the age of "Ome. A similar study by Du *et al*. (2019) at four stages of vegetation recovery found varying fine root biomass, necromass, and total fine root mass. The authors found fluctuations at different points in time that depended on land- and vegetation-related conditions. Thus, the chronosequence of "Ome" at the research site is the key factor controlling the extent of soil ecosystem recovery and fine root biomass (Feng *et al*., 2018). Similarly, in karst forests, disturbances from external factors can color the spatial structure of communities, which can also affect the dynamics of fine roots (Zhang *et al*., 2022). Pioneer vegetation gradually occupies the land in the early years of land abandonment, while fine root biomass is low because the soil nutrient conditions are poor in the karst region (Liu *et al*., 2020). The increase in organic material, the overall microbial activity, and the nutrient availability with time promote the growth of finer roots, the growth of fine roots increases organic carbon accumulation and stabilization of finer material (Prommer *et al*., 2020) contributes to increased soil aggregation. As the former ecosystem restores, the fine root biomass enhances during the "Ome" maturation of 10 to 40 years, when it also reaches the maximum of the succession phase (Cornejo *et al*., 2020).

Just after 1-2 years of disturbances (or activities on a piece of land); the fine root systems recover or increase in size (Cornejo *et al*., 2023). The variation of fine root biomass between three ages of "Ome" can be explained by nutrient content and soil moisture, canopy cover, species composition, aboveground biomass, and tree density (Karki *et al*., 2021). Over longer periods of time, unused land is often recolonized by natural vegetation, including those with fine roots (Singha *et al*., 2020). Ome — at 40 years of age — and under the greater conditions of more vegetative types and a more forgiving ecosystem, fine root growth is much more encouraged. It has been suggested that also in long-abandoned fields, dominant tree species of a mature age have a capacity to gain finer root biomass than younger trees and soils phase fine root biomass is highest at peak stand density (Pei *et al*., 2018). As such, previous research has shown that increasing species richness in an area does not always result in the same increase in fine root biomass (Domisch *et al*., 2015). Nonetheless, Wang *et al*., (2017) additionally argue that topographic features resulting in drier land can also influence fine root growth and survival. Stable soils that are richer in organic matter can promote root development (Huasco *et al*., 2021).

The study result presented in Table 2 indicate that fine root necromass does not show any significant influence across various ages of "Ome"; however, the average necromass increases at the "Ome"age of 40 years. At the "Ome" age of 10 years, the average fine root necromass in transect 1 is 0.198 ± 0.142 g/m², which is considered very low compared to the relatively higher fine root biomass. Necromass in transect 2 significantly increases to 1.415 ± 2.017 g/m², while in transect 3, fine root necromass is recorded even lower at 0.320 ± 0.124 g/m², indicating variation in the number of dead roots or decomposition among younger individuals. At the age of 20 years, fine root necromass experiences a significant increase compared to the age of 10 years. In transect 1, the necromass value reaches 1.474 ± 1.381 g/m², indicating an increase in the number of dead roots. However, in transect 2, the necromass value is even higher at 2.411 ± 1.655 g/m², suggesting that some plants at this age experience more root decomposition. In transect 3, although the necromass value is lower (0.526 ± 0.375 g/m²), the increase compared to the age of 10 years is still clearly evident. At the age of 40 years, fine root necromass reaches its highest value in transect 2, at 1.207 ± 1.714 g/m², although this value is lower than that of transect 2 at the age of 20 years. In transect 1, the necromass value reaches 1.210 ± 0.858 g/m², which still indicates an accumulation of necromass as the age of the plants increases[10]. In transect 3, the necromass value is 1.315 ± 0.944 g/m², which is still higher compared to the "Ome" ages of 10

and 20 years, although lower than in the other transects at the "Ome" age of 40 years.

Overall, this study demonstrates that the age of "Ome" has a significant influence on the amount of fine root necromass. More necromass of fine roots appears at an older plant age, finished up during the stage "Ome" with 40 years old is characterized with greater processes through root decomposition (Pan *et al*., 2022). As per Liu *et al*., (2018), the largest quantity of necromass in a region is ascribed to root senescence and the very low rate of decay during winter that occur because the temperatures during winter are low. Overall, the absence of impact on fine root necromass results from a range of factors underlying root dynamics, decomposition cycles and soil ecosystem stability (Li *et al*., 2020). It is a kind of karst area with calcareous soil condition and high pH, which makes it difficult for plants to absorb nutrients, especially essential elements in calcareous soil, causing that older roots die faster (Peng and Chen, 2021). This root death process adds to the pool of fine root necromass (Andrade *et al*., 2021).

The total root mass over time since land abandonment (land abandoned for 10 years or 40 years): Root biomass spectrum varies based on forest type, and it varies significantly during the entire process of land abandonment. The oldest “Ome” age(40-year-old) has a wide range of vegetation, which may point to the fine root production of “Ome” ages being larger than that of the other “Ome” ages. This can be affected by environmental factors, including soil physical properties, nutrients, temperature, moisture, and light (Fang *et al*., 2025). According to Tasser *et al.* (2021) more abundant trees (e.g. apple dominance) are associated with more total root mass, and climate affects soil development and fertility, regulating ecological and physiological processes at the tree and the stand level that govern fine root dynamics of growth and mortality (Wang *et al*., 2017). The differences in the biomass of active and passive fine roots (necromass) in primary forests are influenced by similar mechanisms. Abiotic factors (temperature, water and nutrient content in the soil) directly affect bottom-up processes, such as the accruals of tree biomass in the developing canopy over time (Yazaki *et al*., 2016).

Different plant species have developed different root queuing strategies, which determine the fine root functional properties (Tian *et al*., 2024). Differences in fine root biomass among stand ages could be related to various factors, such as canopy cover and tree density (Wambsganss *et al*., 2021). Li *et al*., (2021) say elevated acid soil concentrations add pressure to other soil components, promote fine root death, and even contribute to declines in fine root biogenesis. Moreover, interspecies competition is known to affect fine root traits (Wei *et al*., 2024). Based on this potential, in younger areas, the "Ome" age decides how deeply rooted the root systems are. So, that leads to more competition for water, in the long term, cutting up for the root system which can help in the disparity of the tree species root depth distribution during the early growth stage (Domisch *et al*., 2015).

***Soil chemical properties and fine roots*:** Fine roots affect soil carbon flux from aboveground parts by rapid turnover. Assefa *et al*. (2017) emphasized that fine roots (the ones with diameters below 2 mm) are key drivers in soil ecosystems, with fundamental roles in stabilizing soils as well as fuel biogeochemical processes (Cornejo *et al*., 2020). Moreover, more complex roots: fine root biomass (living roots), fine root necromass (dead roots), and their associated mass, can independently and dramatically affect soil’s physical and chemical properties (Weemstra *et al*., 2020). Living roots promote microbial activity and soil mitigation, and dead roots add organic matter, which is essential for long-term soil fertility. That rocky substrate at the research site allows X environmental conditions that restrict plant rooting. Soil’s physical and chemical properties can influence fine root biomass since karst areas generally contain less nutrients than land of other types (Pan *et al*., 2018).

Belowground biomass negatively correlates with soil NH_4^+, NO3, and C (Table 3) at the "Ome" age (i.e., at the age of 20 years). The negative correlations between fine root biomass and these soil properties are likely due to active roots taking up nitrogen in these forms, which decreases concentration in the soil. This corresponds with the data from Cai *et al.* (2019) suggesting a negative correlation between fine roots with soil nutrient concentrations, e.g., carbon and nitrogen. Availability of nitrogen is another important factor driving the vertical distribution of the fine roots (Su *et al*., 2019). Li *et al*. (2021) stated that the absorption of nitrogen through the leaves can increase the plant's nutrient acquisition and enhance the amount of carbon that promotes fine root growth. Transport of nutrients other than NO3− is therefore also influenced by an increase in SO_4^-, PO_4^-, K^+, and Mg^{2+} that should show a negative correlation at the same time with high fine root biomass (Singha *et al*., 2020). In contrast, nitrogen becomes available due to the reduction of fine root biomass. In older recovering forests, high nitrogen mineralization with greater fine root mass positively correlates with nitrogen mineralization and promotes the nitrogen cycle acceleration (Wang *et al*., 2024). At the same time, soil carbon (C) increases by the accumulation of organic matter from root necromass to maintain the balance of the carbon cycle in the soil. Karst areas are associated with decreased carbon content largely owing to the restrictions imposed by soil and vegetation (Huang *et al*., 2021). However, fine-root biomass is particularly important for soil ecosystem balance, because of their prominent role in soil organic matter formation and nutrient uptake (Pei *et al*., 2018). Under "Ome" age of 20 years, fine root biomass provide the ability to modify the amount of NH_4^+ and NO_3^- forms of N in soil through a more stable nutrient cycle. The roots are fine and dense, facilitating the absorption of nutrients, including nitrogen in NH_4^+ and NO_3^- forms. According to Morikawa *et al*. (2022) inorganic

forms of nitrogen such as ammonium (NH_4N) and nitrate (NO_3N) are readily absorbed by plants and are susceptible to competition in nitrogen-deficient ecosystems.

The fine root biomass is not significantly affected by other factors, such as pH, organic carbon, total nitrogen, total P_2O_5, available phosphorus, macronutrient content (e.g., nitrogen, phosphorus, and potassium), and base cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+), but they still show a positive and negative correlation with fine root biomass. The PCA analysis in Figure 3 shows the correlation of the fine roots with the physical-chemical properties of the soil. No marked differences are seen at the "Ome" ages of 10 and 40 years. Overall, very little soil-plant correlation was found in fine root biomass at 40; this lack of relationship could be a result of limited growth activity by plants after decades of nutrient depletion. However, nutrient absorption capacity in older roots is weaker, and root system efficiency for nitrogen content regulation may decrease (Chen *et al.*, 2020). In contrast, the so-called "Ome" age of 10 years in plants, a period during which they are yet to attain optimal growth stages, or the development of their finely branched roots may not be perfected. The difficulties in detecting these relationships could be due to other considerations (e.g., plant acclimation or biotic interactions) (Wei *et al.*, 2024). The weak correlation concerning soil parameters may also attribute to karst landform nature of the site, where the availably of nutrients is very limited (Bai *et al.*, 2021). Interplay between fine root traits and environment is commonly weak particularly in karst land, which was proposed to be attributed to divergent selection on fine roots (Bowsher *et al.*, 2016). In an ecosystem where fine root production, biomass, and necromass are high, but fine root biomass and necromass are low, the fine root system is inclined to renew the turnover rate of older fine roots (Pan *et al.*, 2022). High turnover of fine roots (short lifespan) is important sustain high absorption efficiency and cycling of nutrients. According to Kulmatiski *et al.* (2017) instead of absorbing nitrogen and phosphorus fine roots cycle them quickly in nutrient-limited soils.

Fine root necromass as well as total fine root mass affect the physical-chemical dynamics of the soil (Pan *et al.*, 2022). In this study, there existed no significant relationships for necromass nor total fine root mass for any of the "Ome" ages. Yet, the values of correlation in Table 3 indicate all these parameters are relevant for the presence of the necromass and total mass. Soon after land abandonment, root necromass starts to decompose and nutrients (e.g., nitrogen (N), phosphorus (P), and organic carbon) are released and made available to the soil (Pan *et al.*, 2022). In this regard, soil in karst regions improve with time as root necromass accumulation represents an input of organic matter, promotes the mineralization process of nitrogen and improves the cation exchange capacity (CEC) of the soil (Pan *et al.*, 2022). This will help the soil to retain the nutrient compounds needed for plant growth and release them in ionic form. Soils with high CEC have a higher fertility content because they can hold more nutrient ions, while soils with lower CEC have a lower absorption capacity for cations such as K^+, Ca^{2+}, and Mg^{2+}. Soil with higher clay fraction and organic matter content is more likely to retain nutrients and water, encouraging the proliferation of fine roots in the soil profile (Rai *et al.*, 2024). Conversely, more coarse-textured soils with lower organic matter produce soil nutrient and water stress, which restricts fine root proliferation and elevates the rate of root mortality such that asymptotic root necromass exceeds that of root biomass. According to Xu *et al.* (2020) fine root biomass and root necromass rises with stand age.

Conclusions: Fine root biomass production in the "Ome" system varies with field age, with older fields (40 years) exhibiting higher soil pH, NO_3^- levels, and significantly greater root biomass and total root mass compared to younger fields (10 and 20 years). Root biomass is positively correlated with soil chemical properties such as NH_4^+, NO_3^-, pH, organic carbon, and nutrients like CEC, K, and P, indicating that improved soil conditions-specially in older fields-enhance root development and productivity, even in marginal soils like karst.

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Availability of data and material**:** The data is available with the corresponding author which can be made available on reguest

Consent to participate**:** All participants consented for this reseaach study.

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SDGs addressed**:** No poverty, zero hunger, good health and well-being.

Policy referred**:** Indonesia's National Land Use and Agricultural Policy; Regulation on Forest and Land Rehabilitation (Rehabilitasi Hutan dan Lahan - RHL), 3. Local Customary Land Use Policies (Adat); 4. Indonesia's Policy on Karst Landscape Protection

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